

# LCM2: A Coupled Leaf/Canopy Radiative Transfer Model

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*Two radiative transfer models have been coupled to generate vegetation canopy reflectance as a function of leaf chemistry, leaf morphology (as represented by leaf scattering properties), leaf thickness, soil reflectance, and canopy architecture. A model of radiative transfer within a leaf, called LEAFMOD, treats the radiative transfer equation for a slab of optically uniform leaf material, providing an estimate of leaf hemispherical reflectance and transmittance as well as the radiance exiting the leaf surfaces. The canopy model then simulates radiative transfer within a mixture of leaves, with each having uniform optical properties as determined by LEAFMOD, assuming a bi-Lambertian leaf scattering phase function. The utility of the model, called LCM2 (Leaf/Canopy Model version 2), is demonstrated through predictions of radiometric measurements of canopy reflectance and sensitivity to leaf chlorophyll and moisture content. ©Elsevier Science Inc., 1999*

## INTRODUCTION

The ecological sciences community is beginning to use remote sensing data, in particular data on vegetation canopies, for dealing with regional to global environmental issues (Sellers et al., 1995). The use of remote sensing data offers the advantage of current and synoptic information based on observations of vegetation canopies

from airborne or satellite sensors. Satellite-based vegetation indices are widely used to infer approximate canopy biomass and condition in ecosystem process models that estimate nutrient allocation and gas exchange by plants and soil. Process model predictions have been found to be highly sensitive to estimates of the amount of intercepted photosynthetically active radiation (IPAR) by a canopy, implying that improved IPAR estimates from satellite imagery would yield more accurate estimates of greenhouse gas fluxes and overall biomass (Baret and Guyot, 1991; Goward, 1991). Additional information that could potentially be derived from satellite imagery, especially concerning canopy chemistry, could help refine these models (Potter, 1996). For example, the decomposition rate of leaf litter in soil is known to depend sensitively on cellulose and lignin concentrations, while nitrogen concentration is an indicator of potential carbon fixation (Field and Mooney, 1986).

Various approaches to determine the underlying biophysical or ecological state variables responsible for specific dynamic responses of vegetation to various environmental stimuli have been proposed. In particular, modeling continues to play a central role in the investigation of these responses. Canopy reflectance models, such as SAIL (Verhoef, 1984) and THREEVEG (Myneni and Ross, 1991), and leaf radiative transfer models such as PROSPECT (Jacquemoud and Baret, 1990) and LIBERTY (Dawson and Curran, 1998), have been developed to address fundamental research issues in remote sensing and ecology. Reflectance modeling is a necessary component of scientific investigation that establishes diagnostic links between investigative conjecture and spectral data collected in the laboratory and field or through remote sensing. For example, models can be used to test the apparent relationship between leaf protein content and spectral derivatives at the leaf and canopy levels (e.g., Yoder and Pettigrew-Crosby, 1995; Johnson and Billow,

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1996), since protein concentration and other critical factors, such as leaf thickness and canopy architecture characterization, can be controlled by the investigator. Models can also provide further insight into the relationship between IPAR and leaf area index (LAI) or specific leaf area (SLA), allowing investigators to evaluate the accuracy and robustness of current and proposed information extraction algorithms.

A within-leaf radiative transfer model called LEAFMOD (Leaf Experimental Absorptivity Feasibility MODEL) (Ganapol et al., 1998) was developed to investigate the feasibility of estimating biochemical content of vegetation through spectral profiles of reflected light ultimately detected from air- or space- born imagery. Features of the model include a consistent radiative transfer characterization of photon scattering within a homogeneous leaf, rather than the commonly used two-stream or plate approximations. The model can be applied either in forward or inverse modes, both of which will be required for the leaf/canopy model discussed below. With an average leaf thickness, specific absorptivities, a scattering coefficient and concentrations for the major biochemical constituents, LEAFMOD (in the forward mode) provides leaf hemispherical reflectances and transmittances and the directional distribution of the radiance exiting the leaf surfaces. In this way, a leaf scattering characterization (or leaf phase function) can be constructed that will serve as input to the vegetation canopy model to be described.

An existing dense canopy model, called CANMOD (Ganapol and Myneni, 1992), was modified to incorporate the leaf as an active scattering element. The radiative transfer formulation for a turbid medium treats the canopy as a "cloud of leaves" and serves as the basis for the investigation of the factors influencing canopy reflectance. The model features interleaf scattering with the radiance obtained using an adaptation of the analytically based FN method. Characterization of the leaf angle distribution by standard distributions, (e.g., erectophile, planophile, etc.), allows for a variety of canopy architectures to be investigated. In the canopy model considered here, a bi-Lambertian leaf phase function is assumed which incorporates representative leaf scattering hemispherical reflectances and transmittances as estimated through LEAFMOD. At this time, CANMOD does not include the hot spot effect since only one angle radiative transport is considered and the experiment to which model results will be compared minimized this effect. The hot spot will be included in a later, more comprehensive, model.

In this presentation, we describe a canopy reflectance model that is explicitly dependent on leaf level information. Model confirmation is through sensitivity studies as well as comparisons of predictions to experiment. In the future, the model is intended to be an es-

sential component of an overall inversion to detect canopy attributes remotely.

## INTEGRATED LEAF/CANOPY RADIATIVE TRANSFER MODEL: LCM2

### General Description

In the approach taken in developing LCM2, the assumption of a bi-Lambertian leaf phase function allows for the incorporation of leaf reflectances and transmittances (from LEAFMOD) characteristic of various degrees of environmental stress, canopy health, and leaf thickness. With these quantities, the canopy model (CANMOD) then simulates the top-of-canopy reflectance.

Both the leaf and canopy radiative transfer models are based on the FN method of solution of the 1-D radiative transfer equation originated by Siewert et al. (1986). The leaf optical properties, obtained from LEAFMOD, define the bi-Lambertian phase function used to describe photon scattering between leaves in the canopy. The leaf scattering profile required by LEAFMOD is empirically inferred from an exact inversion using measured reflectance and transmittance data and the thickness of a reference leaf. The leaf absorption profile is constructed from biochemical concentrations, and specific absorptivities of chlorophyll and carotenoids, protein, lignin and cellulose, and water. Canopy architecture is characterized through idealized leaf angle distributions (LADs). In addition, the canopy leaf area index (LAI) and the soil reflectance are required as input to the canopy model.

A unique feature of LCM2 is the direct incorporation of the intraleaf radiative transfer model, LEAFMOD, to provide leaf optical properties. The canopy reflectance for a mixture of plant communities, each with different leaf spectral properties, LADs, and LAIs, can also be simulated.

### Radiative Transfer within a Canopy: CANMOD

Radiative transfer within a vegetation canopy is markedly different from conventional radiative transfer because of the influence of leaf orientation. The distinctive feature of the leaf as a scattering center is the dependence of the distribution of scattered photons on the orientation of the leaf area responsible for scattering. This is unlike conventional radiative transfer in which spherically symmetric scattering centers are assumed and, therefore, their orientation plays no role (rotational invariance). For this reason, the leaf orientation in a canopy is characterized through the leaf angle distribution (LAD) defined as

$$g_L(\Omega_L)d\Omega_L = \text{the fraction of all leaves whose upward normal falls within the solid angle } d\Omega_L.$$

From this definition, the intercept function  $G$ , representing the total leaf area intercepted by photons in the di-

rection  $\Omega$  from leaves of all directions, can be defined as in Eq. (1):

$$G(\Omega) \equiv \int_{4\pi} d\Omega_L g_L(\Omega_L) |\Omega_L \cdot \Omega|. \quad (1)$$

$\Omega$  is the photon direction and is specified by the inclination (or direction cosine)  $\mu$  with respect to canopy depth and the azimuth angle  $\varphi$ . If a leaf, oriented in the direction  $\Omega_L$ , is assumed to deflect photons from a direction  $\Omega'$  into the solid angle  $d\Omega$  about  $\Omega$  with probability  $\gamma(\Omega', \Omega; \Omega_L)$ , the appropriate canopy (area) scattering phase function for leaves of all orientations is given by Eq. (2) (Ross, 1981):

$$\Gamma(\Omega', \Omega) = \int_{2\pi} d\Omega_L |\Omega \cdot \Omega_L| g_L(\Omega_L) \gamma(\Omega', \Omega; \Omega_L). \quad (2)$$

With these definitions, the one-dimensional (in canopy depth) radiative transfer equation describing photon interactions within a canopy for an azimuthally averaged canopy is written as (Ganapol, 1990)

$$\left[ \mu \frac{\partial}{\partial \tau} + G(\mu) \right] I(\tau, \mu; \mu_0) = \int_{-1}^1 d\mu' \Gamma(\mu', \mu) I(\tau, \mu'; \mu_0). \quad (3)$$

Here  $\tau$  is the longitudinal photon position measured in units of LAI and  $\mu$  is the inclination with respect to the canopy depth coordinate. The azimuthally averaged area scattering phase function,  $\Gamma(\mu', \mu)$ , is of the form

$$\Gamma(\mu', \mu) = \int_{-1}^1 d\omega g_L(\omega) a(\mu', \omega) b(\mu, \omega), \quad (4a)$$

where an azimuthally uniform LAD [ $g_L(\Omega(\omega, \varphi)) \equiv g_L(\omega)$ ] has been assumed. The quantities  $\mu'$  and  $\mu$  are the photon direction cosines before and after a scattering event respectively.

A bi-Lambertian leaf scattering leaf model, where the leaf scatters as an idealized surface, is assumed (Shultis and Myneni, 1988), leading to

$$\begin{aligned} a(\mu, \omega) &= \tau_L H(\mu, \omega) + \rho_L H(-\mu, \omega), \\ b(\mu, \omega) &= 2H(\mu, \omega), \end{aligned} \quad (4b)$$

where  $\rho_L$  and  $\tau_L$  are the leaf reflectance and transmittance respectively and

$$H(\mu, \omega) \equiv \frac{1}{2\pi} \int_{(+)} d\varphi |\Omega \cdot \Omega_L|.$$

The integration is over the range of  $\varphi$  for which the integrand remains positive.

A beam source inclined in direction  $\mu_0$  is assumed to fall on the top surface of a canopy of infinite transverse and finite longitudinal extents giving the entering radiance

$$I(0, \mu; \mu_0) = \delta(\mu - \mu_0). \quad (4c)$$

At the canopy/soil interface, the boundary condition is given in Eq. (4d):

$$I(\Delta, -\mu; \mu_0) = 2r_s \int_0^1 d\mu \mu I(\Delta, \mu; \mu_0), \quad (4d)$$

where  $r_s$  is the soil reflectance and  $\Delta$  is the canopy LAI.

The application of the FN method gives an analytical representation of the exiting radiances in terms of a series expansion with unknown coefficients. Once these coefficients have been found through matrix inversion, the canopy reflectance factor is obtained by integration over all view directions

$$R_f = \frac{1}{\mu_0} \int_0^1 d\mu \mu I(0, -\mu, \mu_0); \quad (5)$$

and the nadir reflectance factor is defined as

$$R_{nf} \equiv I(0, -1; \mu_0) / 2\mu_0.$$

The method has been implemented in the FORTRAN77 programming language in a module called CANMOD.

## IMPLEMENTATION OF LCM2

In LCM2, LEAFMOD is coupled to CANMOD through the leaf reflectance and transmittance in the leaf (bi-Lambertian) phase function as given by Eqs. (4a) and (4b) (see flow chart in Fig. 1). Recall that the leaf condition defines the optical properties upon which the canopy reflectance will depend.

### Specification of a Leaf Angle Distribution (LAD)

Of most immediate concern for the appropriate implementation of any canopy model is the generation of the necessary model input data including the leaf optical properties and LAD. In LCM2, a variety of LADs are permitted in an order to account for our general ignorance of canopy architectural variability. Because we are dealing with natural diversity, the specification of a continuous function ( $g_L$ ) for the LAD is highly unrealistic but convenient since data for LADs are not generally available. The inclusion of the LAD is a modeler's attempt to capture the influence of canopy architecture on canopy reflectance. For this reason, the LAD represents the least certain of the modeling parameters. In LCM2, the canopy architecture for dense vegetation is represented by a selection of continuous functions. The available choices are (Ross, 1981):

LAD	$g_L(\omega)$ , $\omega = \cos(\theta)$
Planophile	$\frac{4\omega^2}{\pi\sqrt{1-\omega^2}}$
Erectophile	$\frac{4(1-\omega^2)}{\pi\sqrt{1-\omega^2}}$
Plagiophile	$\frac{16\omega^2(1-\omega^2)}{\pi\sqrt{1-\omega^2}}$
Extremophile	$\frac{(16\omega^4 - 16\omega^2 + 4)(1-\omega^2)}{\pi\sqrt{1-\omega^2}}$
Unophile (spherical)	1

Each LAD is also shown in Figure 2.

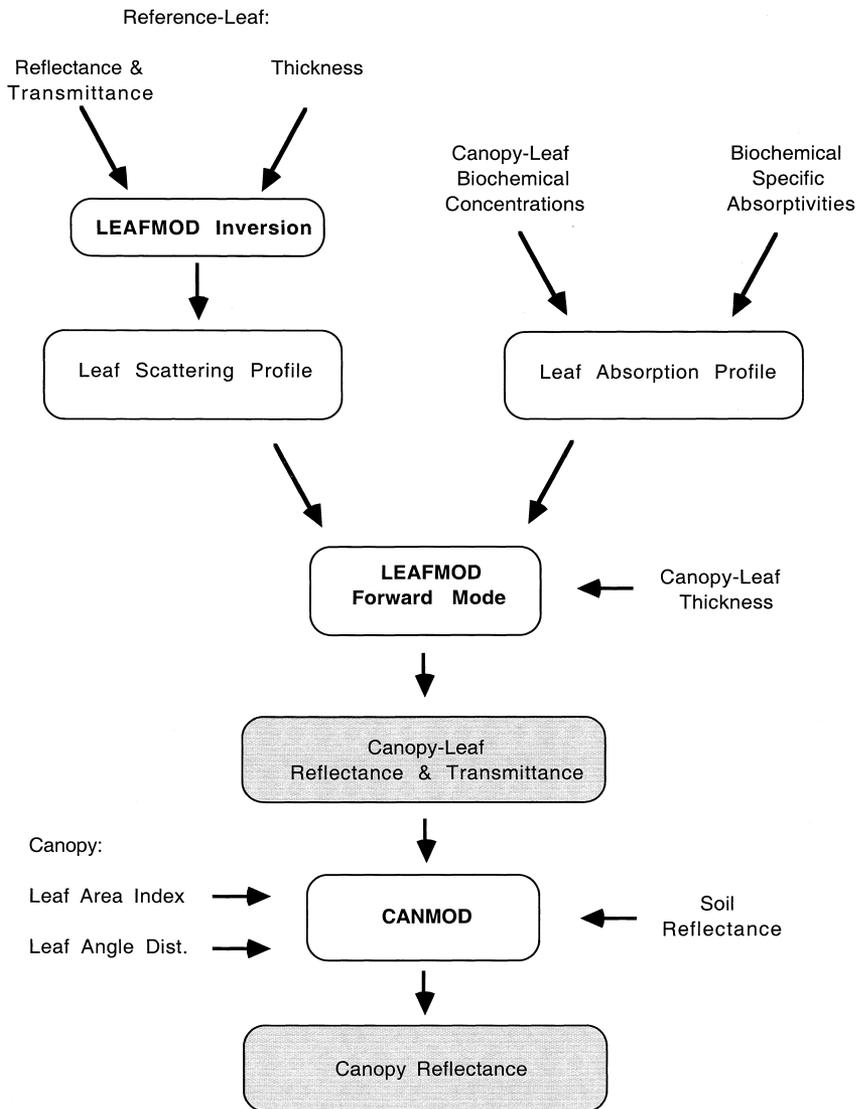


Figure 1. Flow chart for operation of LCM2.

### Estimation of the Scattering Coefficient

As indicated above, the leaf scattering properties to be input into the canopy model are obtained directly from the LEAFMOD inversion. The inversion procedure has been described in detail in Ganapol et al. (1998) and will only briefly be described here.

The key feature of the proposed incorporation of LEAFMOD data into the canopy model is avoidance of the need to specify a general theory of within-leaf scattering. Since leaf scattering depends on the species and the density of the refractive cell-wall discontinuities as well as the cell-wall configuration, a general scattering theory for leaves is difficult, if not impossible, to construct. Hence, unlike the PROSPECT (Jacquemoud and Baret, 1990) and the LIBERTY (Dawson and Curran, 1998) leaf models, no leaf scattering model is postulated *a priori* (scattering from plates or spheres). Rather, the leaf scattering and absorption coefficients are determined in the LEAF-

MOD inversion from actual leaf reflectances, transmittances, and leaf thickness. Photons are assumed to obey the true radiative transfer equation for isotropic scattering. This avoids the need to introduce modeling parameters (such as "N" in prospect) in order to characterize an assumed scattering model. In this way, a physically meaningful scattering coefficient profile is generated such that the radiative transfer equation is always satisfied.

Since LEAFMOD is executed in the inverse mode for a representative canopy leaf of interest to generate a spectral scattering profile, the availability of spectral reflectance and transmittance measurements and thickness of a reference leaf is required. Spectral measurements for many common species can be obtained from the LOPEX leaf data set (Hosgood et al., 1995) or, if a spectrophotometer is available, generated as needed. Both the total-leaf scattering and absorption coefficients will then

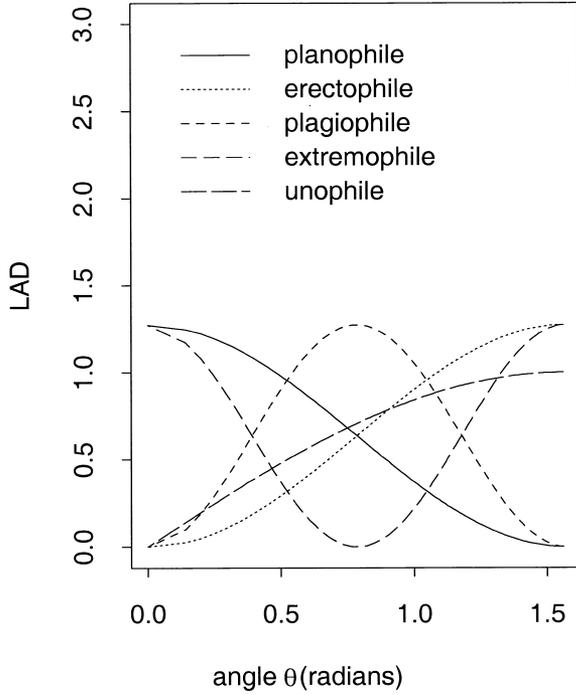


Figure 2. Five theoretical LADs implemented in LCM2 with the ordinate specifying  $g_L(\theta) \equiv g_L(\omega) |d\omega/d\theta|$ . The curves show the fractional percentage of leaves with normals in the range  $d\theta$  with respect to nadir. Each LAD has one or two extrema. For example, the planophile leaf normals are mostly close to nadir.

be known for the reference leaf at each wavelength. Only the scattering coefficient profile, however, will be retained for further use.

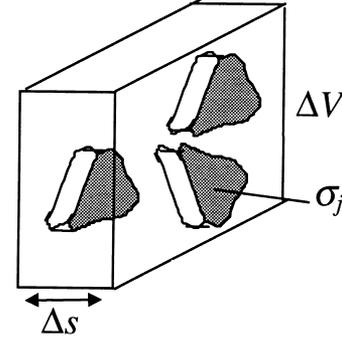
The specification of the scattering coefficient through inversion is a unique feature of LCM2. The use of the reference leaf scattering coefficient for the canopy leaf of interest is based on the origin of within-leaf scattering. Photon scattering within a leaf is controlled primarily by the leaf anatomy associated with the internal cell-wall structure of a particular species. Thus, because of the similarity of the anatomical structure of the reference and canopy leaves, their scattering properties should be similar, at least to a first approximation, assuming the selected reference leaf is of the same or a similar species as the canopy leaf under investigation.

### Specification of the Absorption Coefficient

An appropriate leaf absorption profile is constructed for the canopy leaf of interest from the specific absorptivities (Jacquemoud and Baret, 1996) of the biochemical constituents (including water) and their specified area concentrations (mass/leaf area). For example, let  $\sigma_j$  be the specific absorptivity for photon absorption in biochemical

agent  $j$  (of density  $\rho_j$ ) in units of effective absorbing area per gram of leaf material. Then the total area contained in a homogeneously mixed leaf volume  $\Delta V$  (of arbitrary orientation) responsible for absorption in agent  $j$  along the photon path  $\Delta s$  (shown below) is

$$A_j = \rho_j \Delta V \sigma_j = \rho_j A \Delta s \sigma_j$$



where  $A$  is the area for the leaf volume  $V$ . Thus, the probability of photon absorption in element  $j$  is the ratio of the area available for interaction with agent  $j$  to the total area  $A$  available for all interactions

$$\rho_j = \frac{A_j}{A} = [\rho_j \Delta s] \sigma_j.$$

The concentrations  $\rho_j$  are specified as appropriate for the investigation of a canopy of a particular biochemical composition. The probability per pathlength of absorption [or the absorption coefficient (in units of  $\text{cm}^{-1}$ )] for agent  $j$  is therefore

$$\Sigma_j \equiv \frac{\rho_j}{\Delta s} = \rho_j \sigma_j.$$

For  $J$  biochemical agents, the total absorption coefficient is the sum of the individual biochemical absorption coefficients

$$\Sigma_a \equiv \sum_{j=1}^J \rho_j \sigma_j. \quad (6)$$

Equation (6) therefore allows the construction of an absorption coefficient for specific canopy conditions as prescribed through the variation of the biochemical concentrations. For all agents except water, the density is determined from the mass concentration ( $\rho_A$ ) as

$$\rho_j = \frac{\rho_{Aj}}{d_L}.$$

For water, since  $\sigma_w$  is already the absorption coefficient,  $\rho_w$  is the leaf moisture fraction.

### Determination of the Canopy Reflectance

From Eqs. (4a) and (4b), the CANMOD area scattering phase function is seen to require the leaf exitances ( $\rho_L$ ,

Table 1. Variation of the Number of LAD Inclination Discretizations (LMC)<sup>a</sup>

LMC	Unophile		Erectophile		Plagiophile	
	$R_f$	$T_n$	$R_f$	$T_n$	$R_f$	$T_n$
12	0.1704	0.7670	0.1478	0.7945	0.2154	0.7058
18	0.1699	0.7665	0.1477	0.7944	0.2152	0.7056
24	0.1698	0.7664	0.1477	0.7944	0.2153	0.7057
30	0.1697	0.7664	0.1477	0.7945	0.2153	0.7058
40	0.1696	0.7663	0.1478	0.7945	0.2154	0.7058

<sup>a</sup>  $R_f$  and  $T_n$  are the canopy reflectance and transmittance, respectively.

$\tau_L$ ). To generate the appropriate reflectance and transmittance for the canopy leaf, LEAFMOD is used in the forward mode with the predetermined scattering and absorption coefficients as found above. These exitances are then input into the bi-Lambertian phase function of CANMOD [Eq. (4b)] to form the complete LCM2 leaf/canopy model. In this way, one has control over the leaf optical properties and thickness for analysis purposes. Several leaf optical property data sets can be input into the canopy model to simulate a multispecies community or, alternatively, the inclusion of the same species for a variety of LADs. Once the leaf data have been assembled, the canopy reflectance from Eq. (5) can be determined.

The FN numerical method used by LCM2 to obtain the necessary radiances will now be briefly described. The evaluation begins with the discretization of the LAD inclination [ $\omega = \cos(\theta)$ ] as the abscissa of an appropriate quadrature. Two coupled singular integral equations for the exiting radiances can be rigorously derived from Eq. (3). The singular nature of the integral equations requires special attention for their solution. By application of the FN method (Ganapol and Myneni, 1992), the exiting radiances are obtained as an expansion in shifted Legendre polynomials of the form given in Eqs. (7a) and (7b):

$$I(0, -\mu; \mu_0) = \sum_{a=0}^{N-1} a_a P_a(2\xi - 1), \quad (7a)$$

$$I(\Delta, \mu; \mu_0) = \delta(\mu - \mu_0) e^{-\Delta/\xi_0} + \sum_{a=0}^{N-1} b_a P_a(2\xi - 1), \quad (7b)$$

with

$$\xi \equiv \mu/G(\mu), \quad \xi_0 \equiv \mu_0/G(\mu_0).$$

The blending coefficients  $a_a$  and  $b_a$  are determined by matrix inversion after application of a collocation procedure. Using these coefficients in a postprocessing algorithm, the reflected radiance,  $I(0, -\mu; \mu_0)$ , is obtained. Finally, the canopy reflectance is determined by numerical integration from Eq. (5) using a shifted Gauss/Legendre quadrature.

The implementation of the FN method requires a numerical quadrature for evaluation of the matrix elements needed in the solution as well as discretization of the leaf LAD inclination. Both these numerical approximations incur numerical error. Table 1 shows the influ-

Table 2. Input Parameters for LCM2

Leafmod Input	
$rfd$	Leaf thickness (cm)
$r_1$	Protein concentration ( $g/cm^2$ )
$r_2$	Cellulose plus lignin concentration ( $g/cm^2$ )
$r_3$	Water fraction
$r_4$	Chlorophyll concentration ( $\mu g/cm^2$ )
$R_f, T_f, dref$	Reference leaf exitances and thickness
Specific absorptivities	
CANMOD Input	
LAI	Leaf area index
LAD	Planophile, erectophile, plagiophile, extremophile, unophile
$r_s$	Soil reflectance
$\mu_0$	Cosine of solar zenith
LMC	Number of leaf inclinations (quadrature order) (12)
LM	View quadrature order (12)

ence of discretizing the LAD inclination (order LMC) on the canopy reflectance and transmittance ( $R_f, T_n$ ) for three LADs. The canopy characteristics are, LAI=1,  $\rho_L = \tau_L = 0.45$ , and  $r_s = 0$ . From the table, it is observed that almost four-digit accuracy is achieved with as few as 12 angles. A similar study (not shown) indicated a quadrature order of 12 is appropriate for convergence of the matrix elements to 3 or 4 digits. Based on these studies, a 12-angle LAD discretization and quadrature order will be assumed sufficient to provide at least 3-digit numerical accuracy of the results to follow.

## DEMONSTRATION: STATIC SENSITIVITY STUDY

A demonstration of the operation of LCM2 is presented in this section through a sensitivity study. The sensitivity study concerns variation of canopy reflectance with respect to leaf biochemical concentrations and is included as a partial confirmation of the model and also to indicate how LCM2 can be used as an investigative tool. The required inputs are given in Table 2. This demonstration and the validations to follow use the specific absorptivities (Jacquemoud et al., 1996), as determined for the PROSPECT model (v.2.01), multiplied by a factor of 2. Since the PROSPECT model is based on a Kubelka–Munk two-stream theory, the conversion from flux to radiance involves a factor of 2 when comparing absorption coefficients. Thus, the justification of the factor of 2 comes from radiative transfer theory (Ishimaru, 1978) and is most dramatically borne out observationally as well.

The amount of chlorophyll and water were varied from nominal values for a dense (LAI=10) sycamore maple canopy. Figure 3a shows the canopy response in the visible wavelengths as the chlorophyll content is reduced

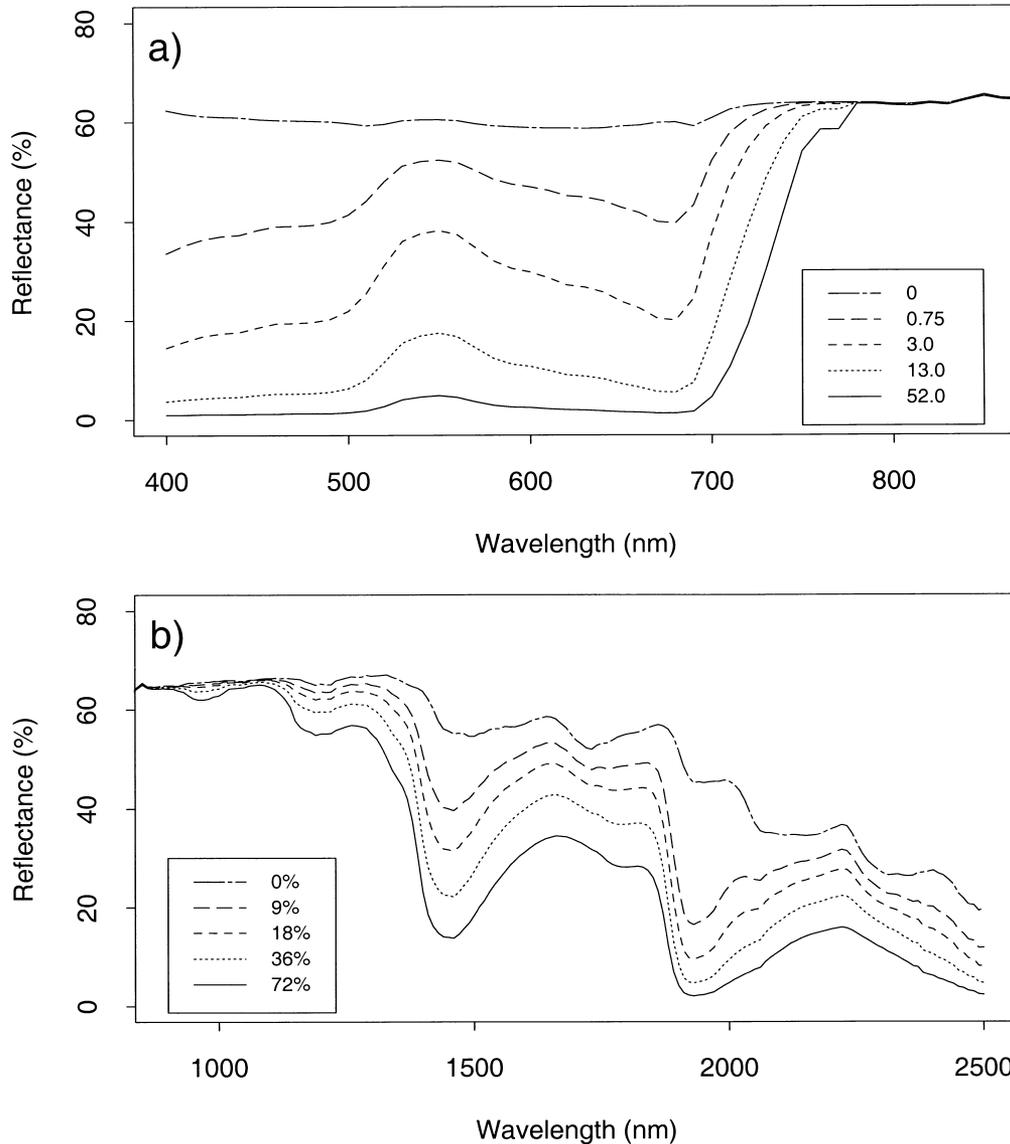


Figure 3. Simulated reflectance of a dense (LAI=10) sycamore maple canopy: a) foliar chlorophyll concentrations ranging from  $52 \mu\text{g}/\text{cm}^2$  to zero, b) water fraction ranging from 72% to zero.

from a measured value of  $52 \mu\text{g}/\text{cm}^2$  to zero. A planophile canopy was assumed with measured moisture content of 72%. As expected, the visible reflectance increases as the chlorophyll decreases. When the water concentration is reduced from 72%, the canopy reflectance in the NIR increases, again as expected (Fig. 3b). Note the emerging spectral detail as the canopy dries out. Also note, in both cases, the nonlinear relationship between absorber concentration and reflectance amplitude.

#### EXPERIMENTAL CONFIRMATION

To provide further confirmation of the performance of LCM2, model output was compared to spectral measurements for the following empirical studies:

1. Leaf Optical Properties EXperiment, or LOPEX (Hosgood et al., 1995);
2. Douglas fir needle-leaf and canopy spectra of Dungan et al. (1996);
3. Bigleaf maple canopy spectra (Yoder and Pettigrew-Crosby, 1995).

The LOPEX archive includes leaf hemispherical reflectance and transmittance data for 38 fresh dicot and monocot species, along with a comprehensive set of associated biophysical and biochemical measurements. Fresh and dry leaves from this dataset were, in fact, used to derive specific absorptivities for PROSPECT (Jacquemoud et al., 1996) that have here been adopted as input to LCM2.

The Douglas fir and maple experiments were origi-

Table 3. Species Used for Spectral Reconstruction of LOPEX Fresh-Leaf Measurements

1. Oak	20. Wild vines (grape)
2. <i>Pseudo acacia</i>	21. Walnut
3. Chestnut	22. Apricot
4. Hazel	23. Sage
5. Laurel	24. <i>Prunus</i>
6. Maize	25. Red oak
7. Alfalfa	26. Birch
8. Sorghum	27. Alder
9. Sunflower	28. Willow
10. Soy	29. Reeds
11. Poplar	30. Banana
12. Clover	31. Elm
13. Maple	32. Grape
14. Ash	33. Fig
15. Linden	34. Bamboo
16. Beech	35. Ivy
17. Potato	36. Palm
18. Nettles	37. Tomato
19. Mulberry	38. Grape (white)

nally undertaken to explore the spectral effect of fertilization at leaf and canopy levels. The two studies, highly similar in measurement approach, are suitable for LCM2 confirmation for the following reasons:

1. The seeding canopies were mono-specific and included no understory.
2. A turntable was used to provide azimuthal averaging with respect to illumination and measurement.
3. Canopies of various LAI were studied.
4. Leaf reflectance and transmittance and canopy reflectance were acquired from the same set of (Douglas fir) trees.
5. The soil reflectance was measured.

A reasonably comprehensive set of leaf chemical and physical measurements were taken in both studies. However, to fully parametrize the model, it was necessary to use measurements from LOPEX and other studies or to make assumptions.

All simulations were run on a Silicon Graphics Challenge “L” workstation with 128 MB RAM. A running time of approximately 2 min was required to simulate leaf and canopy spectra throughout the 400–2500 nm spectral region at 10 nm intervals (211 wavelengths).

### LOPEX: Spectral Reconstruction of Leaves

LCM2 was used to reconstruct the measured fresh-leaf reflectance and transmittance of 38 species from the LOPEX data set (Table 3). A scattering profile was derived for each species through model inversion on mean measured spectra. An absorption profile was generated for each case from measured biochemical concentrations and leaf thickness. These profiles were then used in forward model for leaf-level spectral simulation.

Overall agreement between the reconstructed and measured spectra was evaluated as the root-mean-square-error (*RMSE*):

$$RMSE = \sqrt{\sum_{\lambda} [MOD(\lambda) - OBS(\lambda)]^2 / n} \quad (8)$$

where *MOD* is the modeled response at wavelength  $\lambda$ , *OBS* is the measured response at wavelength  $\lambda$ , and *n* is the number of wavelengths (in this case,  $n=211$ ). The *RMSEs* for these reconstructions ranged from 0.5% to 2.2% for reflectance and 0.7% to 2.7% for transmittance. This performance is similar to *RMSEs* of “generally less than” 3% as found with PROSPECT reconstruction of the LOPEX data set (Jacquemoud et al., 1996). The low *RMSE* values for this simplest test demonstrates the stability of LCM2 in the forward and inverse modes, and also support the validity of building absorption profiles from specific absorptivities and constituent concentrations.

### Maple Canopy Nadir Reflectance

LCM2 was used to simulate broadleaf canopy nadir reflectance using the input contained in Table 4a. The leaf scattering profile was derived from LOPEX spectral measurements of fresh sycamore maple leaves. Model output was compared to nadir reflectance measurements

Table 4a. Model Input for Bigleaf Maple Canopy-Level Simulations

	Fertilization Level			Source <sup>a</sup>
	Low	Medium	High	
Leaf				
Pigments ( $\mu\text{g cm}^{-2}$ )	29.1	37.8	52.8	1, 2
Protein ( $\text{g cm}^{-2}$ )	0.000384	0.000646	0.000922	1 (assumes TN*6)
Water fraction	0.723	0.723	0.723	2
Lignin+cellulose ( $\text{g cm}^{-2}$ )	0.00121	0.00121	0.00121	2
Thickness (cm)	0.0094	0.0094	0.0094	2
Canopy				
LAI	0.9, 1.7, 3.1	3.2, 5.7, 10.8	3.6, 5.5, 10.8	1
LAD	Planophile	Planophile	Planophile	Assumed
Soil reflectance factor	0.03	0.03	0.03	1
$\mu_0$	0.829	0.829	0.829	1

<sup>a</sup> Sources: (1) Yoder and Pettigrew-Crosby (1995); (2) LOPEX dataset (Hosgood et al., 1995).

Table 4b. RMS Errors (%) of LCM2 Prediction vs. Canopy Reflectance (Yoder and Pettigrew-Crosby, 1995)<sup>a</sup>

<i>Fert trmt:</i>	(F)	(H)	(Q)
Low	4.7	2.8	3.7
Medium	2.4	2.4	3.5
High	6.2	2.8	2.5

<sup>a</sup> Canopies were organized as Full (F), Half (H) and Quarter (Q) density groupings of bigleaf maple seedlings.

of bigleaf maple seedling canopies (Yoder and Pettigrew-Crosby, 1995) (Figs. 4a–c). In that study, seedlings were cultivated under three fertilization treatments to induce differences in foliar pigment and protein concentration; canopies were organized as full, half, and quarter density groupings to produce a wide range in LAI per treatment (Table 4a). RMS errors were reasonably low, ranging from 2.4% to 6.2% (Table 4b). This exercise provides an example of driving LCM2 with substitute leaf measurements acquired from an independent data set.

### Douglas Fir: Leaf Reconstruction and Canopy Prediction

Spectral reconstruction of leaf reflectance and transmittance, measured on Douglas fir needles by Dungan et al. (1996), was performed using the input parameters given in Table 5a. Comparisons of reconstructed and measured spectra are displayed in Figures 5a–c. RMS errors of 1.6–3.9% (Table 5b) were somewhat larger than with the LOPEX subset above, with an overall tendency toward model underestimation of the observed. Still, the results suggest LCM2 performs reasonably well for spectral reconstruction of needle leaves.

Canopy nadir reflectance simulations, based upon the Douglas fir leaf reconstruction above and canopy parameters of Table 5a, are compared to the canopy nadir reflectance measurements of Dungan et al. (1996) in Figures 6a–c. In that experiment, two nadir-viewing spectro-radiometers (GER SIRIS, Millbrook, NY and

Table 5b. RMS Errors (%) LCM2 Prediction vs. Measured Douglas Fir Leaf Hemispherical Reflectance, Transmittance, and Canopy Reflectance (Dungan et al., 1996)<sup>a</sup>

<i>Fert trmt:</i>	<i>Leaf Refl.</i>	<i>Leaf Trns.</i>	<i>Canopy (G)</i>	<i>Canopy (S)</i>
Low	2.7	3.9	8.7	5.5
Medium	1.6	3.1	11.7	7.3
High	2.0	2.6	5.9	4.4

<sup>a</sup> Canopy measurements were made simultaneously with GER (G) and Spectron (S) spectroradiometers.

Spectron SE590, Denver, CO) acquired top-of-canopy data simultaneously from adjacent vantage points, yet with somewhat different fields-of-view. The Spectron measurements shown here are the mean of ~900 spectra per canopy; the GER measurements are the mean of ~30 spectra per canopy.

In general, the GER measurements were high with respect to those of the Spectron, a discrepancy that was unresolved in the original study. In addition, reflectance measurements by both instruments were high compared to those of other needle-leaf canopies reported in the literature, which Dungan et al. (1996) attribute to the use of seedlings rather than mature trees.

RMSEs for the Douglas fir canopies ranged from 4.4% to 11.7% (Table 5b). The modeled and Spectron reflectances agree well in the visible. However, the modeled red edge occurs at somewhat longer wavelengths than observed by either instrument, and simulations are lower than measurements throughout the near-infrared. These discrepancies indicate that an intervening shoot model may be required to properly characterize clumped needle scattering.

### CONCLUSIONS

A coupled leaf/canopy radiative transfer model, LCM2, has been constructed to simulate canopy reflectance as determined by foliar concentrations of pigments, protein,

Table 5a. Model Input for Douglas Fir Leaf- and Canopy-Level Simulations

	<i>Fertilization Level</i>			<i>Source<sup>a</sup></i>
	<i>Low</i>	<i>Medium</i>	<i>High</i>	
Leaf				
Pigments ( $\mu\text{g cm}^{-2}$ )	49.7	55.1	99.2	1,2
Protein ( $\text{g cm}^{-2}$ )	0.00111	0.00146	0.00238	1 (assumes TN*6)
Water fraction	0.582	0.586	0.581	1
Lignin+cellulose ( $\text{g cm}^{-2}$ )	0.00352	0.00352	0.00378	3 (assumes cell=lignin)
Thickness (cm)	0.038	0.038	0.038	Bond (unpublished meas.)
Canopy				
LAI	2.8	2.7	2.3	1
LAD	Planophile	Planophile	Planophile	Assumed
Soil reflectance factor	0.03	0.03	0.03	1
$\mu_0$	0.574	0.574	0.574	

<sup>a</sup> Sources: (1) Dungan et al. (1996); (2) LOPEX dataset (Hosgood et al., 1995); (3) Johnson et al. (1994).

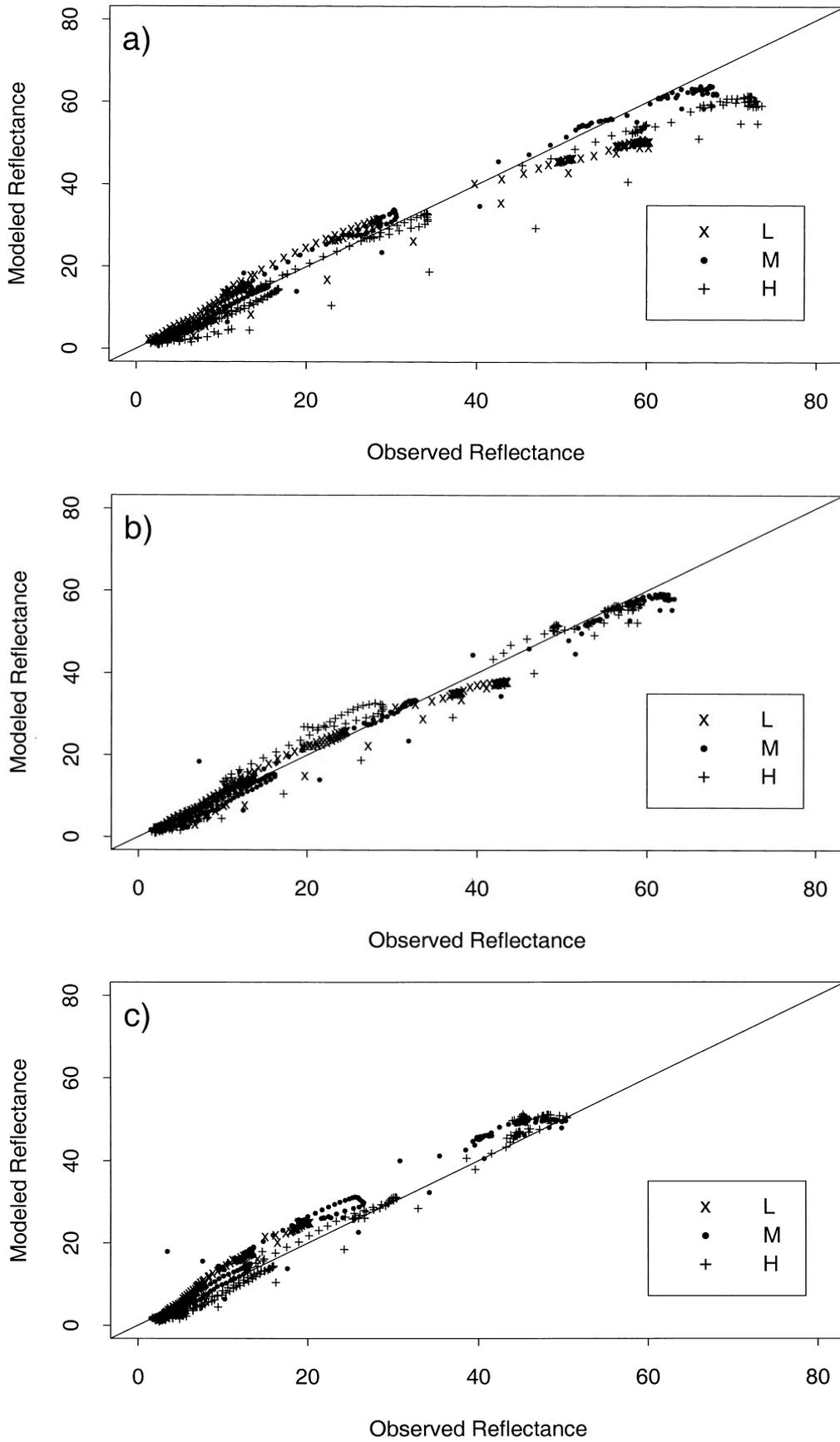


Figure 4. Observed vs. modeled reflectance (%) for low, medium, and high fertilization maple seedling canopies. All spectra 400–2500 nm with 10 nm steps. Canopy density (LAI): a) Full, b) Half, c) Quarter.

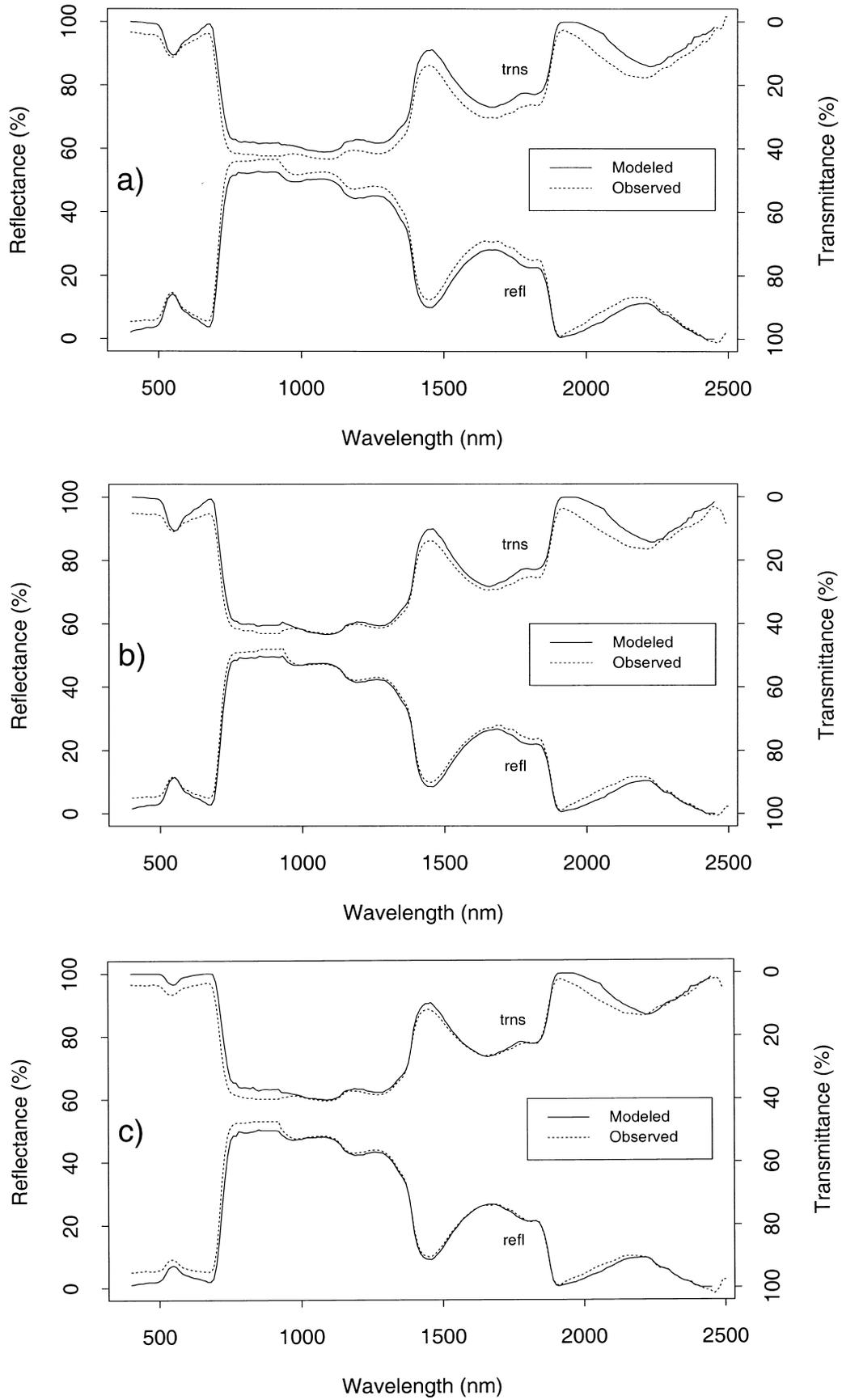


Figure 5. Observed vs. modeled spectra for Douglas fir needle leaves. Fertilization treatment: a) low, b) medium, c) high.

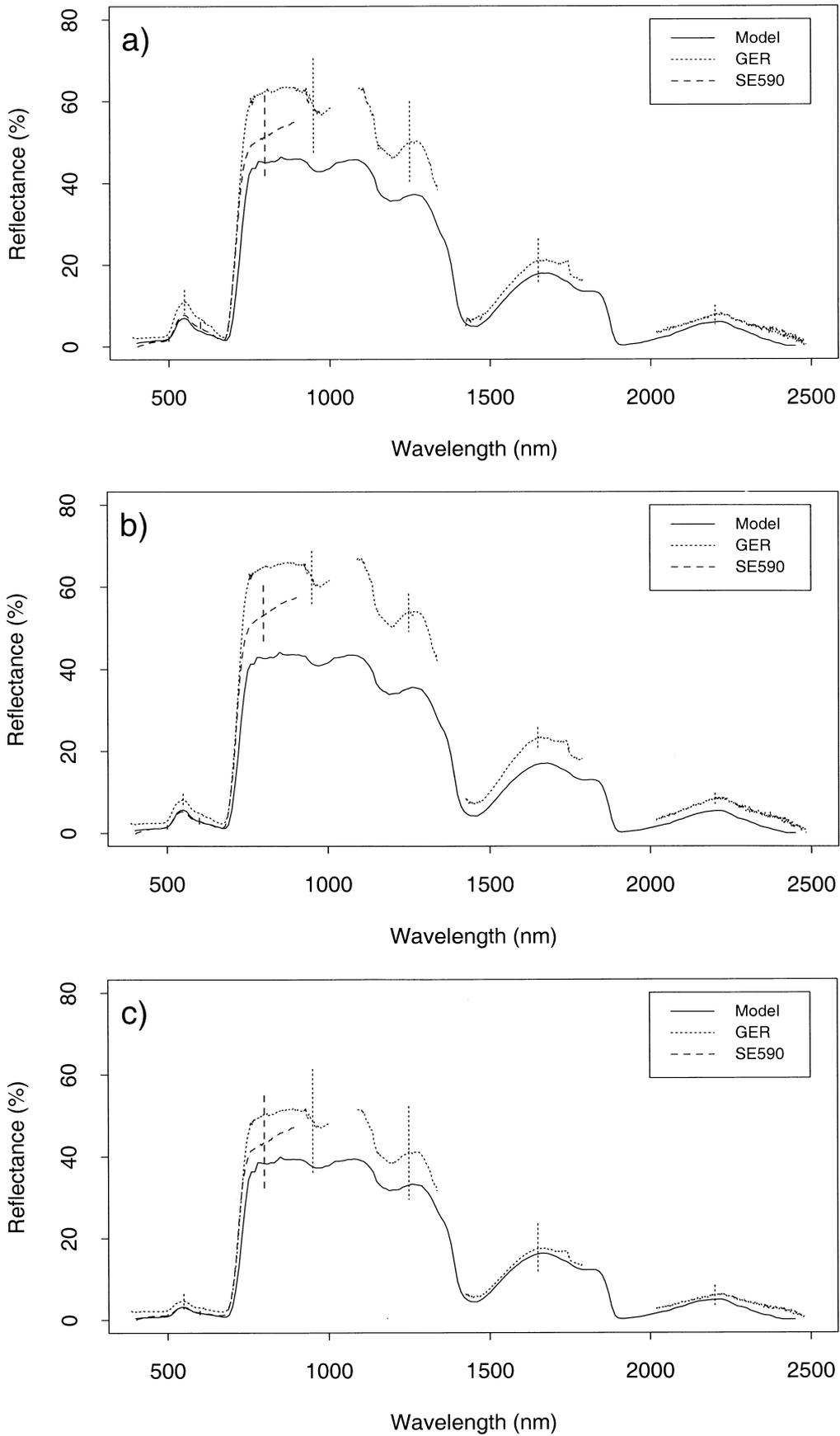


Figure 6. Modeled spectra of Douglas fir seedling canopies vs. observations by GER and Spectron SE590 instruments.  $\pm 1$  standard deviation shown at representative locations by vertical bars. Fertilization treatment: a) low, b) medium, c) high.

structural compounds (lignin and cellulose) and water, leaf thickness, leaf angle distribution, LAI, and soil reflectance. The model was developed by linking LEAFMOD, a model for radiative transfer within leaves, to CANMOD, a canopy radiative transfer model, in such a way as to take advantage of laboratory data on leaf chemistry and spectra to specify canopy scattering and absorbing properties. The LAD of the canopy model allows leaf angles that may be either broadly or narrowly distributed. The canopy model also allows for specification of multiple leaf species to represent, for example, mixtures of stressed or senesced leaves as well as under- and overstory. Vertical stratification of canopy leaf properties to better represent a variety of canopy phenological configurations can also be accommodated.

The main advantage of LCM2 over previously developed canopy reflectance models is the direct inclusion of leaf-level data in the reflectance determination. Specifically, the dependence of canopy reflectance on leaf thickness and condition as indicated by biochemical content can be investigated. Also of particular note is use of the highly accurate FN numerical solution of the leaf and canopy radiative transfer equations. A final distinction concerns the bi-Lambertian leaf scattering model. Since LEAFMOD returns directional information concerning photon-leaf interactions, a more comprehensive model that better approximates leaf scattering could replace the bi-Lambertian model.

LCM2 was used to reconstruct fresh-leaf reflectance and transmittance profiles for 38 different monocot and dicot leaf species, producing *RMSEs* (vs. measured spectral data) of 0.5–2.7%. A sycamore maple leaf scattering profile was used along with measurements of biochemistry and leaf thickness to simulate nadir reflectance of bigleaf maple canopies of varying LAI and fertilization levels (*RMSE*: 2.4–6.2%). The model reconstructed needle-leaf (Douglas fir) spectra with *RMSE* of 1.6–3.9%. The model tended to underestimate measurements of Douglas fir canopy nadir reflectance, suggesting that the model in its current form does not adequately characterize conifer canopy architecture.

Finally, LCM2 is computationally fast and may be well suited to the “virtual laboratory” concept where vegetation spectra can be accurately simulated to test sensor requirements or information extraction algorithms. Because of its analytical basis, the LCM2 algorithm is “embarrassingly parallel” and if reprogrammed for a parallel computational environment would experience near theoretical speedup.

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